New Approach for Efficient Road Maintenance on Urban Expressway Based on HEML (Hanshin Expressway Logic Model)

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***ABSTRACT*:** Hanshin Expressway is an urban expressway network in Osaka-Kobe area accommodating more than 900,000 vehicles per day. Since it is one of the most important transportation infrastructures in the area, the highest level of Rehabilitation and Maintenance (R&M) quality is always required and we have met the need by developing many efficient maintenance methods. However, due to the lacks of the sufficient budget for highway R&M, the highway administration bodies are requested to reduce the expenditures for R&M activities.

Hanshin Expressway has accelerated to develop a new approach for efficient Road R&M after its privatization. In this paper, the logic model for R&M (named HELM; Hanshin Expressway Logic Model), which was developed by the Hanshin Expressway Corporation, is presented to administrate the whole system of R&M activities in an efficient way. This paper presents the risk management diagrams for the highway patrol, by which the administrative bodies can efficiently design the optimal patrol frequency given the predetermined risk levels based on HELM. The paper is concluded by summarizing the ongoing research agenda to improve the HELM throughout the PDCA cycles of the real R&M activities.

KEYWORDS: Logic Model, Rehabilitation and Maintenance, Risk

1. INTRODUCTION

Maintenance of expressways includes various services: maintenance of bridges, tunnels, and other structures; roadway cleaning and inspection for ensuring the safety of road users; maintenance of information systems for providing traffic information continuously; and cleaning of parking and other facilities for the amenity of road users [1]. The road managers are required to keep expressways always in good condition while improving the efficiency of maintenance.

Management systems are being developed recently to improve the efficiency of maintenance work. Kaito et al. [2], for example, modeled the occurrence of road impediments as a Poisson process, proposed a risk management model on impediment occurrence to discuss desirable road patrol strategies that would reduce the cost of patrol, and verified the effectiveness of the model. Aoki et al. [3] modeled the deterioration of lighting in expressway tunnels, and proposed and verified the optimization of tunnel lighting systems in consideration of life-cycle cost and the risk of unlit lights. These studies focused on the efficiency of individual maintenance activities rather than the entire maintenance work.

The authors have developed a maintenance logic model for managing roadway inspection and other routine maintenance that directly affects road users, and proposed a method to perform evaluation and verification appropriately according to the PDCA (plan-do-check-act) cycle [4, 5]. This paper discusses methods to pursue the efficiency and adequacy of maintenance risk management. While the risk is defined in various ways, this paper defines it as the product of the probability of damage and the magnitude of damage. The maintenance risk includes accidents, major repairs, customer complaints, as well as management flaws caused by neglecting inspection, repair, cleaning, and other maintenance work. This study organizes the objectives and measures of maintenance risk management systematically as a logic model and discusses the optimization of maintenance risk levels by using outcome and output indicators. In other words, the risk of high-risk management items can be reduced by raising their maintenance levels, and the level of overly-low-risk maintenance items can be reduced to cut their maintenance cost. As a result, cost reduction can be achieved while suppressing the risk of the entire management items in a balanced manner.

The occurrence of road impediments, such as potholes, fallen objects, and sand, varies with the route. The probability of the road users to encounter impediments can be reduced by increasing the frequency of inspection, which means reducing the time impediments are left unsolved. To reduce the probability of encountering impediments in a reasonably balanced manner, higher and lower inspection frequencies should be applied to heavy- and low-traffic routes, respectively. While defining the risk as the product of the probability of encountering impediments and the volume of traffic, the risk of the entire route network can be suppressed adequately by controlling the risk of each route to achieve its target level. By using a logic model to analyze the relationship between the risk management targets (outcomes), risk management levels (outputs), and maintenance activities (inputs), the adequacy of risk management levels for the entire maintenance and repair work as well as service levels can be discussed comprehensively. This study foresees future commissioning of maintenance and repair work on the basis of specified performance. The study therefore aims to develop a methodology that allows specification of performance based on a clear basis from the viewpoint of adequate risk management.

2. LOGIC MODEL DEVELOPMENT

2.1 Outline of logic model

According to the theory of new public management (NPM) [6], there is always a hypothetical logic that explains what outcomes are intended by the activity of any policy or project. A logic model is a tool to define and show systematically final outcomes, intermediate outcomes required for achieving the final outcomes, and the action required for achieving the outcomes. The final outcomes in the present case include the improvement of customer satisfaction and the reduction of risk that vehicles on the road face. The logic model clarifies the intention of the policy or project to be evaluated by describing what effects are generated and what final outcomes are obtained by conducting the policy or project; this involves description of multiple steps and procedures as well as schematic representation of their mutual relevance [7].

Logic models have been established as a basic rule to support the NPM theory and have been used for carrying out administrative and fiscal reforms. In Japan, the Government Policy Evaluations Act became effective in 2001 and governmental agencies are developing basic plans for evaluating policies. However, systematization of objectives and policies using logic models has not been achieved yet. Some manuals for developing logic models were proposed in the West [8], and logic models have been used widely in particular in Anglo-Saxon nations.

Application of logic models to asset management has been reported in Australia and other nations [9]; to our knowledge, however, there has been no reported logic model specifically designed for asset management. A logic model shows various events (elements) that may occur in the intermediate processes between specific activities and final outcomes, and connects the elements with a single line or multiple lines to clarify the procedure of achieving the outcomes. To indicate the degree of change or improvement in the policy or project, outcomes are presented in multiple steps (for example, intermediate and final outcomes) as shown in Table 1 [7, 8].

Element	Description
Inputs (resources and activities)	Resources and activities (such as fund and manpower) used for carrying out the operation
Outputs (results)	Results obtained by personnel activities
Intermediate outcomes (short-term outcomes)	Short-term outcomes that may result from activities and outputs
Final outcomes (management objectives)	Final objective of the operation. It generally takes a long term to achieve and may be affected by factors external to the operation.

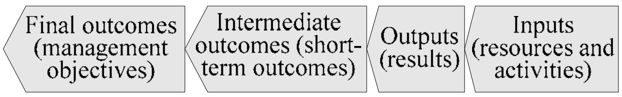

Table 1. Elements of logic model

The logic model has the following features:

- The process between activities (input resources) and final outcomes is shown by connecting the elements with a single line or multiple lines.
- Outcomes are presented in multiple steps.

In this way, the logic model allows us to show the process of deriving outcomes of a policy or project plainly and objectively; otherwise the process tends to be vague.

2.2 HELM construction and indicator setting

It is understood conceptually that routine maintenance is conducted to ensure the safety of road users. Causal relationship in routine maintenance has been recognized on both individual and departmental bases but has not been grasped systematically. As a result, there have some problems: the levels of risk management may vary with the route and time for the same maintenance operation, and conformity in risk management levels may not be achieved between different maintenance operations. With the aim of conducting the risk management of the entire maintenance work effectively, the present study organizes the objectives and measures of the entire maintenance work systematically. The study shows the risk management levels to be achieved and the maintenance operations to be conducted for achieving the levels by using a logic model called Hanshin Expressway Logic Model (HELM). In the HELM, the inputs include routine maintenance operations and their frequency, and the outcomes include the safety of road users. The causal relationships in the intermediate processes are systematically described by using intermediate outcome and output indicators, so as to allow quantitative evaluation as much as possible. A policy evaluation model was developed to evaluate the relationship between inputs and outcomes. The developed HELM is a large-scale model. To outline the configuration of the model, only part of the model is shown in Figure 1 for the sake of brevity.

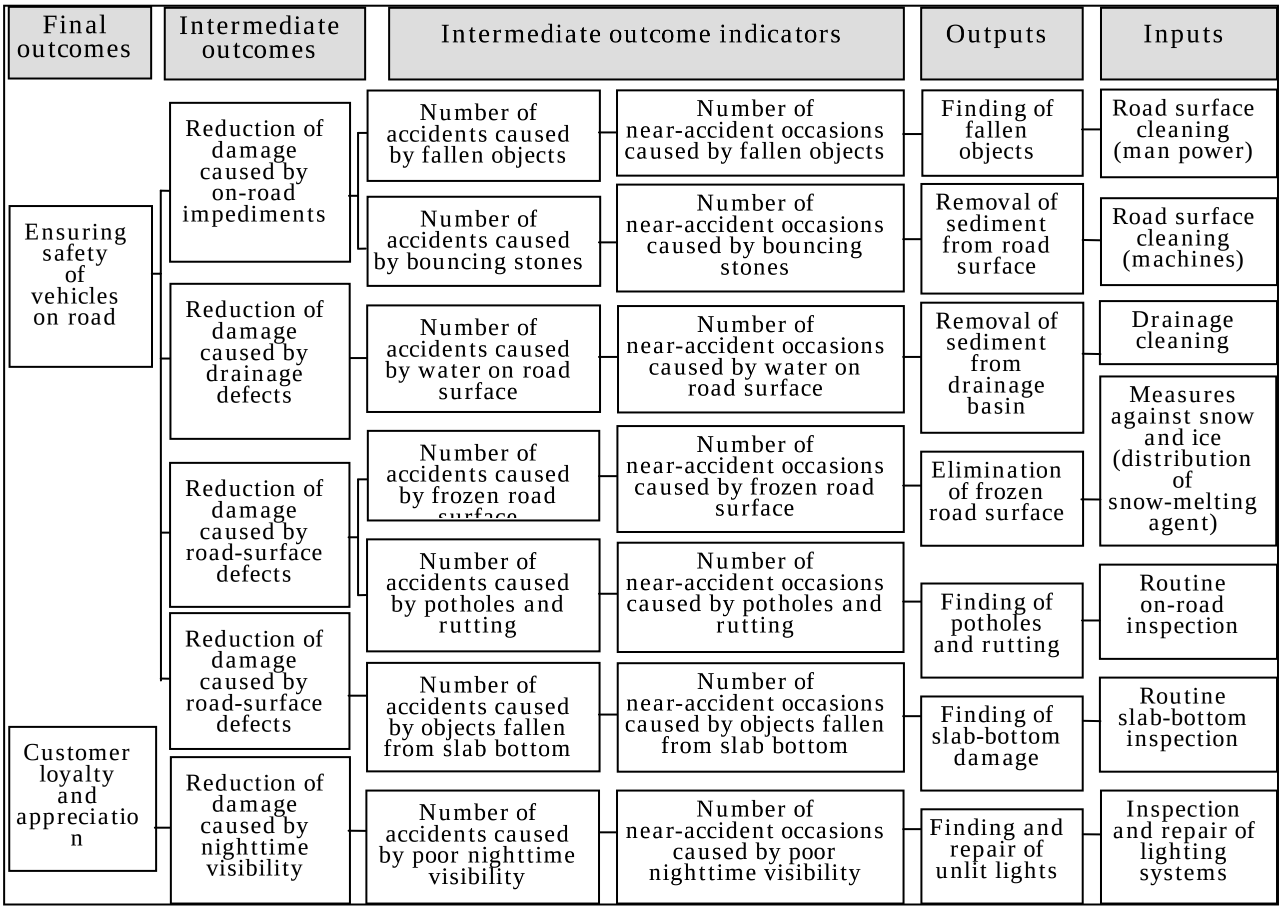

Figure 1. Tree diagram (partial) of Hanshin Expressway Logic Model (HELM)

2.3 PDCA cycle in maintenance

Figure 2 shows the flow of the PDCA cycle, which includes HELM construction, calculation of indicators, and the review of routine maintenance operations. The PDCA cycle of Hanshin Expressway Company Ltd. starts from constructing an HELM. During this stage, it is important to set priorities to intermediate outcome indicators and select inputs that would maximize the performance, with the aim of achieving final outcomes effectively. In the PDCA cycle, the achievement and change of output and outcome indicators are evaluated by regularly measuring the intermediate HELM indicators on a yearly or monthly basis. If any indicator departs from the corresponding benchmark value, the causal relationship between the outcome, output, and input indicators should be reevaluated and, if necessary, the relationship should be revised and inputs selected again. Through the PDCA cycle, the maintenance work can be improved continuously, and accountability to the road users and the public can be strengthened.

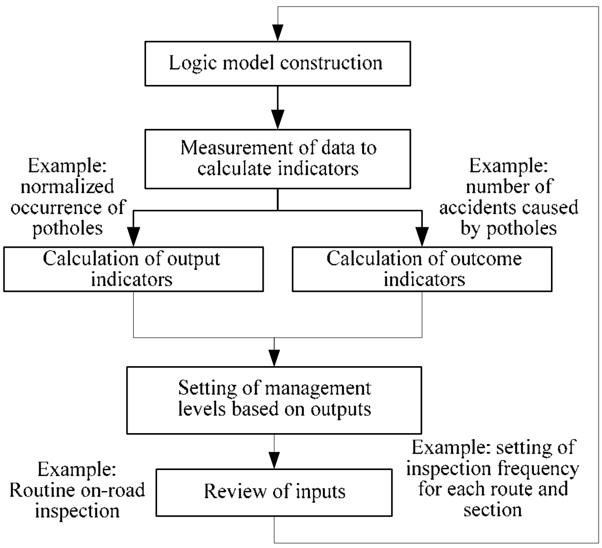

Figure 2. PDCA cycle for maintenance

3. LOGIC MODEL DEVELOPMENT

3.1 Consideration of risk in maintenance

The risk in this study is defined as the product of the probability of damage and the magnitude of damage. The risk in maintenance includes accidents, major repairs, customer complaints, as well as management flaws caused by neglecting inspection, repair, cleaning, and other maintenance work.

Risk levels should be optimized in maintenance risk management. Figure 3 shows schematically the distribution of the risks of management items, before optimization, based on the probability and magnitude of damage. The acceptable zone in the figure indicates the risk management levels that Hanshin Expressway considers desirable. When a current risk is higher than the acceptable range of risk management (i.e., within the risk reduction area), the maintenance level should be raised to reduce the risk. When the risk is sufficiently lower than the acceptable range, the maintenance level can be lowered to reduce the maintenance cost. As a result, we can reduce the risk of the entire management items while reducing the cost.

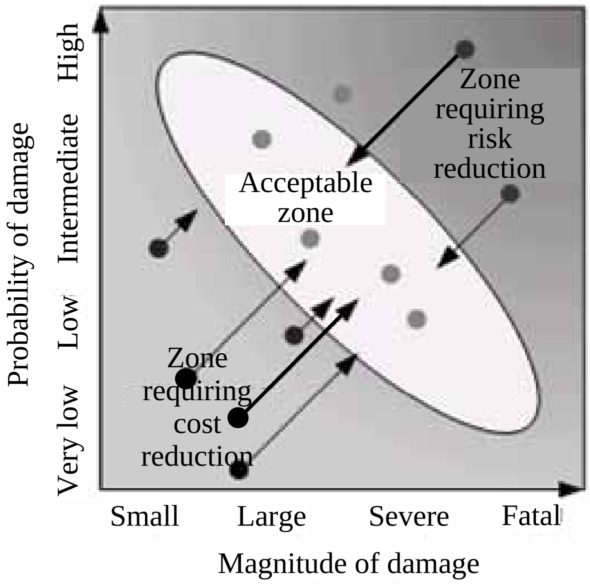

Figure 3. Concept of risk optimization

Because the volume of traffic (magnitude of damage) depends on the route, risk is calculated for each route, and the sum of all the risks is regarded as the risk of the entire route network, which is given by

$$R = \sum_{i} \left(P_i \times C_i \right) \quad (1)$$

Here, R is the risk of a certain management item, P_i is the probability of impediment occurrence for the management item in route section i (i=1, 2,.., n), and C_i is the effect of the impediment occurrence in route section i.

3.2 Method of management level setting

A clear basis is required for setting maintenance levels. Let us concentrate on the final outcome "Ensuring safety of vehicles on road" shown in Figure 1, which is part of the HELM. To achieve the final outcome, the intermediate outcomes such as the occurrence of accidents and management flaws should be reduced or eliminated. It is important to set management levels by using the logic model in relation to the required reduction in the occurrence of impediments (outputs).

For each management item, the relationship between the occurrence of impediments (outputs) and the occurrence of accidents and management flaws (intermediate outcomes) should be surveyed and analyzed for each route, or for each route section more in detail. It is not always possible to obtain deterministic analytical results, such as "accidents or management flaws occur when the number of impediments reaches a certain level." Routes on which no management flaws occurred in a given year can be identified by using accumulated statistic data, and the average risk of such routes can be defined as a management level. In this way, it is possible to conduct management work based on the target "causing no management flaws in the future." The risk management level should be determined in consideration of the risk occurrence properties of the management item. The procedure of setting a risk management level is summarized in Figure 4.

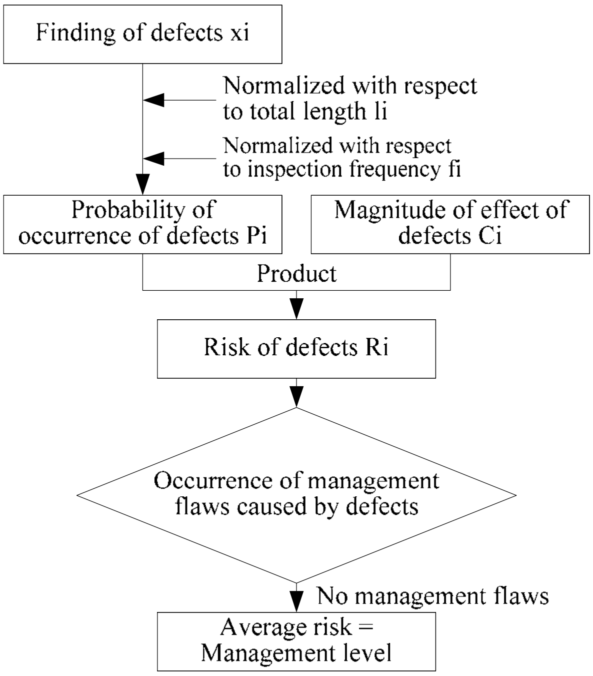

Figure 4. Flow of management level setting

3.3 Risk optimization method

There are two trade-off objectives in risk management: (1) controlling the risk within a desirable range, and (2) reducing the cost of management. These objectives should be pursued under the following conditions.

$$\left| R_{level} - R_i \right| \le R_{margin} \quad (2)$$

$$\sum_i Cost_i' \le \sum_i Cost_i \quad (3)$$

$$\sum_i R_i' \le \sum_i R_i \quad (4)$$

Here, R_{level} is the designated risk management level, R_i is risk for route i, R_{margin} is the margin of the management level, $Cost_i$ is maintenance cost for route i, $Cost_i'$ is maintenance cost after risk optimization for route i, and R_i' is optimized risk for route i.

When determining a risk management level from the occurrence of management flaws, it is difficult to delineate an exact risk level R_{level} below which management flaws will not occur. Therefore, a zone of risk management is defined by setting margins on both safe and unsafe sides of a certain risk level.

The routes that fall within the area A of Figure 5 are considered to be overly managed, and their management levels may be lowered in view of cost reduction. On the other hand, the routes that fall within the area B are overly risky and their management levels should be raised.

There naturally is a trade-off between risk and cost. To reduce risk and cost simultaneously, inputs should be reviewed for each route.

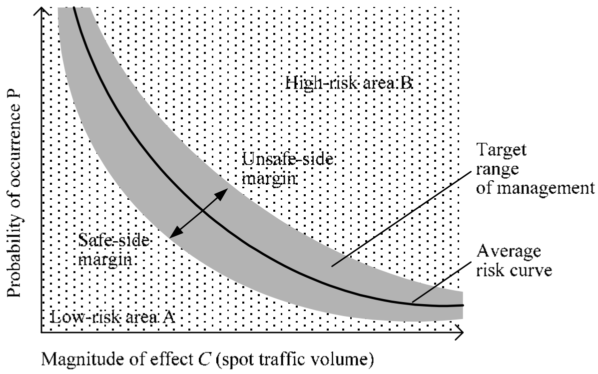

Figure 5. Conceptual diagram of risk curve

4. RISK OPTIMIZATION IN DIFFERENT MANAGEMENT MEASURES (FEASIBILITY STUDY)

4.1 Routine on-road inspection and normalized occurrence of potholes

Among the policy evaluation models that constitute the HELM (see Figure 1), we focus on a model related to potholes (pavement damage requiring urgent repair) found through routine inspection. First, risk management levels for potholes are set by using the logic model.

In the HELM, the frequency of routine on-road inspection is adopted as an input for controlling the risk associated with the occurrence of potholes. The frequency of inspection varies with the route and section, and the frequency in fiscal 2005 was generally two or three times a week. Figure 6 shows the number of pothole occurrences found by routine on-road inspection in fiscal 2002, 2004, and 2005. The figure indicates that the risk of pothole occurrence varies widely with the route and section. The normalized occurrence of potholes, obtained by dividing the number of pothole occurrences by total route length (in km) and inspection frequency, is adopted as an output indicator. Figures 7 and 8 show the data of normalized occurrence of potholes and the flow of setting management levels, respectively.

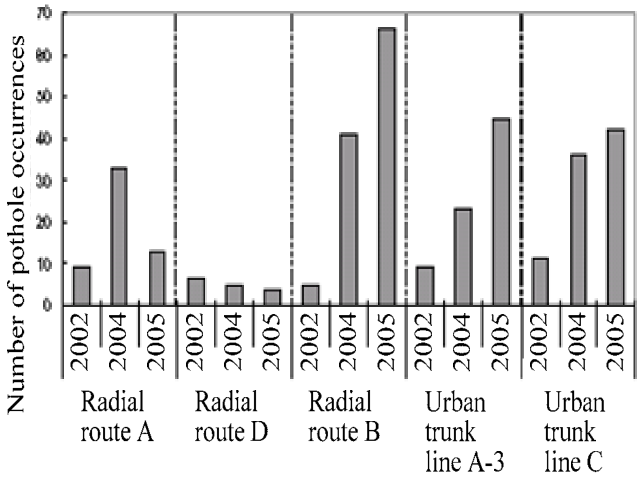

Figure 6. Number of pothole occurrences

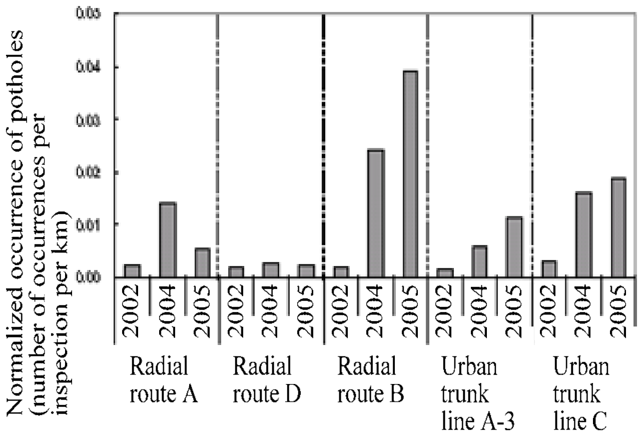

Figure 7. Normalized occurrence of potholes

Because traffic volume varies with the route and section, the effect of potholes (accidents and management flaws) also varies. Considering that the normalized occurrence of potholes represents the probability of occurrence and that traffic volume represents the magnitude of effect, the risk of normalized occurrence of potholes is given by

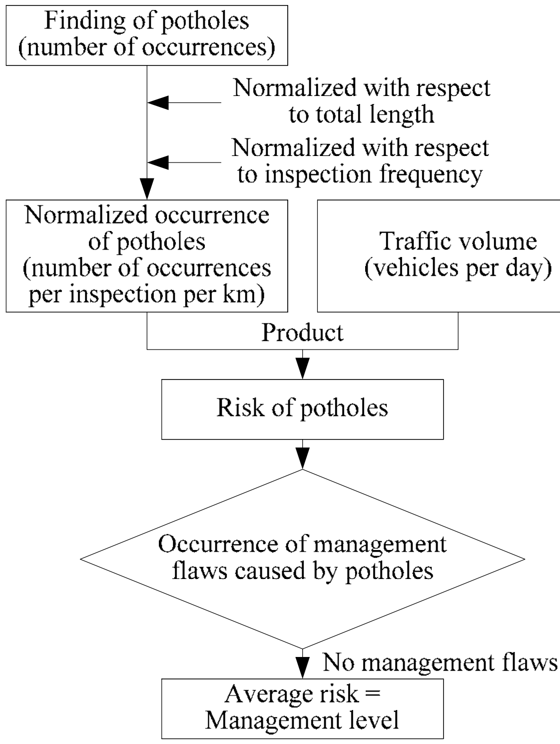

Figure 8. Flow of management level setting (in the case of potholes)

$$R_{pi} = P_{pi} \times C_i \quad (5)$$

Here, R_{pi} is the risk of normalized occurrence of potholes for route i, P_{pi} is the normalized occurrence of potholes for route i, and C_i is the average spot traffic volume in 24 hours. The normalized occurrence of potholes is given by dividing the number of pothole occurrences found through routine on-road inspection in a year by total route length and inspection frequency:

$$P_i = x_i / f_i / l_i \quad (6)$$

Here, x_i is the number of pothole occurrences in a year for route i, f_i is the frequency of routine on-road inspection in a year, and l_i is total route length.

The combinations of normalized occurrence of potholes and spot traffic volume that provide a constant risk of the normalized occurrence of potholes are expressed as a hyperbola (see Figure 5). The area on the upper-right side of the hyperbola is higher in the risk of normalized occurrence of potholes than the management level given by the hyperbola. Once a management level corresponding to a certain risk level is set for the occurrence of potholes, the entire risk can be leveled out by strengthening inspection in appropriate routes and sections.

Risk optimization was attempted with regard to pothole management flaws. The final objective was given as "causing no management flaws in the future," and the management level (intermediate outcome) of Hanshin Expressway was set as "the average risk of routes that have been maintained with no management flaws (32 routes in fiscal 2002, 2004, and 2005)." The management level for the number of pothole occurrences is given by

$$R_{p,level} = \frac{\sum_i R_{p0i}}{n} \tag{7}$$

Here, R_{p0i} is the risk of normalized occurrence of potholes in each route that had no management flaws.

In routes with high risk, inspection frequency is increased to reduce the risk toward the target level. In routes with low risk, inspection frequency is reduced to cut maintenance cost. It is assumed that the number of pothole occurrences in a year is unchanged before and after the optimization, and risk is estimated by changing only inspection frequency. As a result, as shown in Figure 9, the normalized occurrence of potholes in each route fell within the range of risk management.

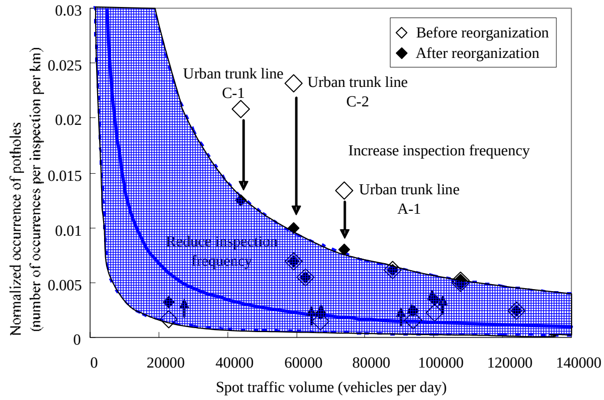

Figure 9. Risk-based reorganization of management

The calculation results in Figure 10 show how the risk of normalized occurrence of potholes and inspection cost in the entire route network are changed by using the above approach of risk optimization. In the present case, both the overall risk and cost were reduced by reorganizing inspection and smoothing out the risk of different routes.

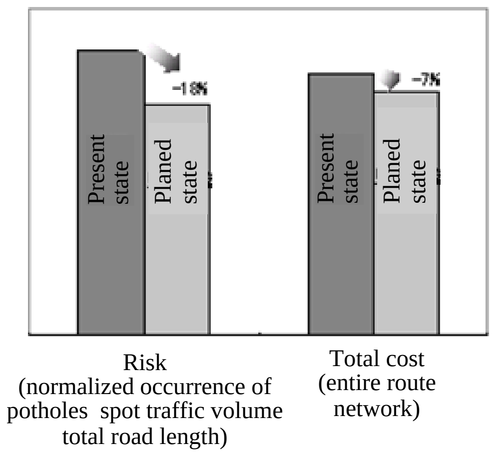

Figure 10. Estimated reductions in risk and cost by reorganization of routine on-road inspection

4.2 Routine slab-bottom inspection and normalized occurrence of slab-bottom damage

We now focus on the optimization of the risk related to slab-bottom damage found by routine slab-bottom inspection. Hanshin Expressway conducts slab-bottom inspection routinely with the aim of avoiding damage to third parties.

The procedure of risk optimization is the same as that for the risk of normalized occurrence of potholes. The frequency of routine slab-bottom inspection depends on the route and section, and the actual annual frequencies in fiscal 2005 were six inspections on land and one inspection above the sea. The output indicator is the normalized occurrence of slab-bottom damage, which is obtained by dividing the number of damage occurrences (requiring urgent repair) found through routine slab-bottom inspection by inspection frequency and the total length (in km) of elevated sections.

An analysis of slab-bottom damage revealed that the number of damage occurrences increased with time elapsed after the completion of upper and lower structures. Damage occurred most frequently in the upper and lower structures completed in the late 1960s (see Figure 11).

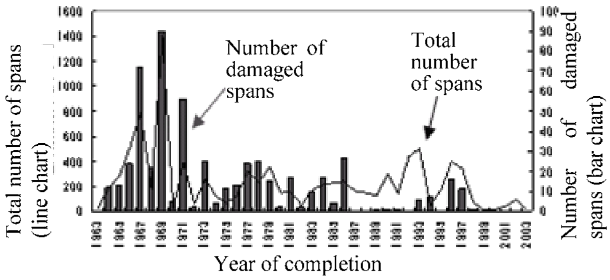

Figure 11. Number of slab-bottom damage occurrences on road sections completed in different years

Because one route may consist of sections constructed in different years, the analysis was done on a section basis. Figure 12 shows the number of slab-bottom damage occurrences and the number of management flaws in each section.

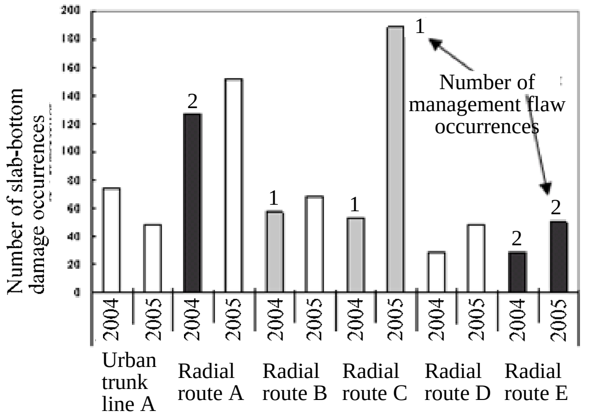

Figure 12. Number of slab-bottom damage occurrences

The risk of slab-bottom damage is defined as

$$R_{ui} = P_{ui} \times C_{ui} \tag{8}$$

Here, R_{ui} is the risk of slab-bottom damage, P_{ui} is the normalized occurrence of slab-bottom damage, and C_{ui} is the total length of elevated sections. The normalized occurrence of slab-bottom damage is obtained by dividing the number of damage occurrences (requiring urgent repair) found through routine slab-bottom inspection in a year by inspection frequency and the total length of sections that may affect third parties. This indicator is expressed as

$$P_{ui} = x_{ui} / f_{ui} / l_{ui} \tag{9}$$

Here, x_{ui} is the number of slab-bottom damage occurrences in a year, f_{ui} is the frequency of routine slab-bottom inspection in a year, and l_{ui} is the total length of sections that may affect third parties. The management level for the normalized occurrence of slab-bottom damage is given by

$$R_{u,level} = \frac{\sum_i R_{u0i}}{n} \tag{10}$$

Here, R_{u0i} is the risk of normalized occurrence of slab-bottom damage in each route that had no management flaws.

The relationship between inspection frequency and the risk of slab-bottom damage was analyzed to see if the risk is within the range of management. In the present case, as shown in Figure 14, both the risk of slab-bottom damage in the entire route network and overall cost were reduced by risk optimization.

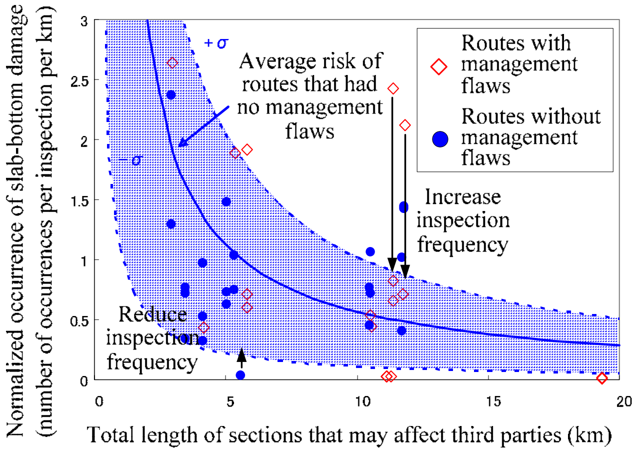

Figure 13. Risk of slab-bottom damage in different road sections

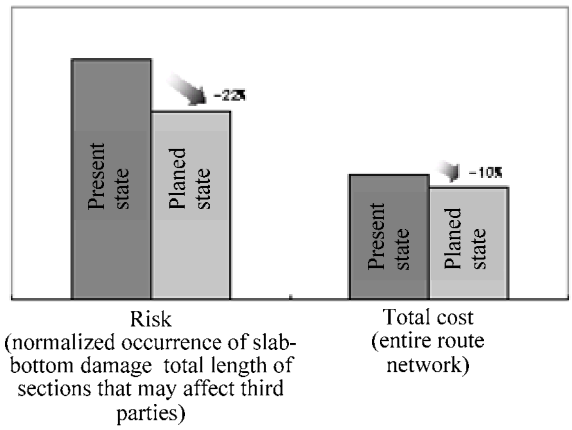

Figure 14. Estimated reductions in risk and cost by reorganization of routine slab-bottom inspection

4.3 PDCA cycle and continuous improvement of HELM

Among management items that constitute the HELM, we focused on the output and outcome indicators related to the risk of pothole occurrence and the risk of slab-bottom damage. We then discussed methods to determine the corresponding management levels. Other than these two items, there are many management items in the HELM. At the present stage, we have developed a primary policy evaluation model pertaining to the causal relationship between many outcome, output, and input indicators that constitute the HELM. Some of the management items are insufficient in data accumulation, and the logic model developed in this study should be considered as a prototype. It is necessary, in the future, to monitor these indicators continuously and evaluate their causal relationship.

5. SUMMARY

A logic model was constructed for the maintenance work of Hanshin Expressway Company Ltd., and a methodology to set risk maintenance levels (output indicator) for risk optimization in routine maintenance was proposed. The study findings are summarized below.

- To manage the maintenance of expressways efficiently, maintenance operations were organized systematically and a logic model specific to Hanshin Expressway (HELM) was constructed.
- A methodology of the PDCA cycle was developed to carry out maintenance work efficiently and effectively by quantitatively measuring the outcome and output indicators of the HELM.
- A method to set risk management levels based on outputs such as the finding of potholes and slab-bottom damage was presented. Instead of delineating an exact risk level, margins were set to define a target range of management in consideration of various uncertainties.
- To control the risk toward the target management level, the frequency of inputs (routine on-road and routine slab-bottom inspection) was reviewed and reorganized. As a result, it was shown that both risk and cost could be reduced.
- As an example of setting management levels for routine inspection, we focused on management

flaws related to potholes and showed an approach of setting a risk management target.

– We presented an objective of suppressing, as much as possible, management flaws that may affect third parties, with regard to setting risk management levels for routine slab-bottom inspection.

As discussed above, risk and management levels should be evaluated in the PDCA cycle by constructing an HELM, reorganizing maintenance operations, and continuously measuring the outcomes. The PDCA cycle allows continuous improvement of maintenance efficiency. The present study has developed an HELM as a prototype model for the causal relationship between intermediate outcomes, output indicators, and input indicators. We need to continue measuring various indicators to improve the logic model and the measuring methods. Because it is expected that performance-specified maintenance services will be ordered more frequently in the future, the issues of setting, measuring, and monitoring adequate risk management levels will become all the more important.

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